102] emmission behavior ~~C3 C13~~ 103] C10 C24
C4 C7 C19 C27 C35 C28 C17
C5 C8 C21 C30 C36 C18
C6 C9 C26 C32 C37
C33 C38
C34 C39-47

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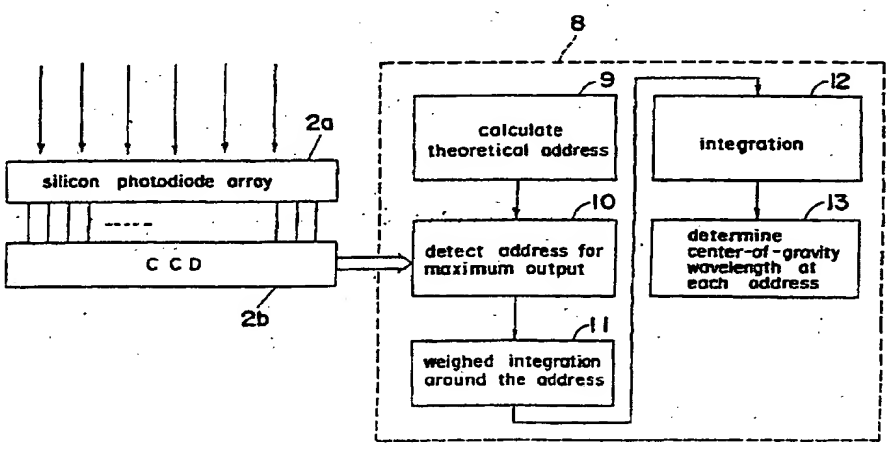
(54) **Method of spectral measurement and spectroradiometer having wavelength calibration function.**

(57) In order to decrease errors in spectral measurement, the data measured at sampling wavelength intervals smaller than the wavelength sampling intervals are changed to data of wavelength sampling interval of spectral effective curve.

If the wavelength half-bandwidths to be measured are different from the wavelength sampling intervals, the spectral data at wavelengths in correspondence with the wavelength sampling intervals are obtained with interpolation.

In a spectroradiometer, wavelength scale is calibrated with use of a plurality of line spectra of specified wavelengths, and the photoelectric outputs are integrated with use of the addresses of elements as a weight factor.

Fig. 5



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BACKGROUND OF THE INVENTION

Field of the Invention

The present invention relates to a method and an apparatus therefor for measuring the spectral distribution of a light source color or an object color, which can be used to evaluate an effective quantity for spectra, such as color or color rendering of light source or colorimetry of object color.

Description of the Prior Art

When spectral measurement is used for evaluating the energy of light source, color and color rendering, and for measuring an object light, it is important to improve the precision of an energy integral in the measurement than the wavelength resolution of spectra. In other words, it is a problem how to measure precisely the energy intensity of radiations at suitable wavelength sections than how to measure a detailed shape of wavelength distribution. This can be solved by making the spectral half-bandwidth correspond to the wavelength sampling intervals used for the measurement.

In a prior art monochrometer of dispersion element drive type such as a prism monochrometer, the dispersion curve agrees with the wavelength scale. Then, the measurement is performed with use of equivalent intervals of a feed of the mechanical width, wherein it is assumed that the differences in dispersion at adjacent wavelength positions to be measured do not change largely each other though the magnitude of linear dispersion varies largely between short and long wavelength portions. Further, in the diffraction grating monochrometer of dispersion element drive type, the dispersion curve is independent of the wavelength scale because a sign bar mechanism is used. However, the dispersion of the diffraction grating monochrometer is rather linear when compared with that of the prism and it is difficult to adjust the slit width mechanically in accordance with a change in dispersion during a spectral measurement. Therefore, spectral measurement is performed by neglecting the change in dispersion.

It is a problem that the above-mentioned monochrometer of dispersion element drive type needs a long time for measurement. Recently, a new spectroradiometer constructed by combining a spectral dispersion optical system and a linear photosensor array becomes available which can measure optical spectra of an object in a short time. However, the mechanical intervals of the photosensor elements which corresponds to measured sampling intervals are independent of the dispersion. Therefore, the nonlinearity of dispersion on the surface on the photosensor element array is large, and the spectral half-bandwidths and the measured wavelength sampling intervals do not agree with each other. Then, the precision of center-of-gravity wavelengths or the precision of wavelength scale is important.

In general, as explained above, wavelength calibration is necessary due to the deviation from the theoretical wavelength in wavelength scale. Previously, in this kind of apparatus, only one wavelength around the center of the wavelength range to be measured is calibrated with a line spectrum or the like, and the center-of-gravity wavelengths of each photosensor element are set by assuming that the intervals of each element are equal to each other. Then, the wavelength sampling intervals deviate so that errors of measurement are large to be used for example for colorimetry. Further, when a plurality of line spectra emitted from a discharge lamp are introduced to a spectroradiometer for calibration at each wavelength position, radiations from the discharge lamp other than those used for calibration or fluctuations of the output of photosensor array are recognized erroneously as the wavelengths of line spectra to be used for calibration.

Further, as explained above, in a spectroradiometer constructed by combining a spectral dispersion optical system and a photosensor element array, the mechanical intervals of the photosensor elements which corresponds to measured sampling intervals are independent of the dispersion. Therefore, the nonlinearity of dispersion on the plane of the linear photosensor array is large and the half-bandwidth of responsivity function (slit function) and the measured wavelength sampling interval do not agree with each other. Thus, the measured center-of-gravity wavelengths deviate from the theoretical center-of-gravity wavelengths to cause mismatching of wavelength. Then, errors are large in a spectral measurement to evaluate the energy, color and color rendering of light source or to measure an object color.

As an example, a mercury line spectrum of 546.1 nm of 100 mW/cm^{-2} is measured when the wavelength half-bandwidths of responsivity function of the monochrometer do not agree with the measured wavelength intervals. As shown in Fig. 1, the responsivity function becomes a trapezoid of 9 nm half-bandwidth if the wavelength width of exit slit is set as 9 nm against 5 nm of the wavelength sampling intervals and 5 nm of the wavelength width of entrance slit. (The scale of irradiance in Fig. 1 is normalized so that the responsivity function of the trapezoid becomes equal to the responsivity function of the above-

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mentioned ideal isosceles triangle.) Then, the measured values of the mercury line spectra at 546.1 nm wavelength of 100 mW/cm^2 are 8, 77 and 40 mW/cm^2 at the sampling wavelengths 540, 545 and 550 nm, respectively, and the measured value of irradiance of mercury line spectrum calculated by a weighed integration becomes 119 mW/cm^2 or the error is 19 % against the true value.

On the contrary, if the responsivity function of monochrometer has a shape of ideal isosceles triangle, the above-mentioned weighed integration can be performed precisely by making the wavelength half-bandwidths of responsivity function agree with the wavelength sampling intervals. In the above-mentioned case, let us assume that a mercury line spectrum at 546.1 nm wavelength is measured when the wavelength half-bandwidth of responsivity function is set as 5 nm. Fig. 2 shows a responsivity function when the measured sampling wavelengths are 545 nm and 550 nm. That is, the wavelength half-bandwidths of responsivity function are set to be equal to the wavelength sampling intervals. If the energy P of the mercury line spectrum is taken as 100 mW/m^2, the measured values can be obtained from Eqs. (1) and (2):

$$P(545) = \frac{550 - 546.1}{550 - 545} \times 100 = 78, \quad [mW/m^2] \qquad (1)$$

and

$$P(550) = \frac{546.1 - 545}{550 - 545} \times 100 = 22. \quad [mW/m^2] \qquad (2)$$

Reversely, if P is estimated from the measurement values P(545) and P(550) by using mensuration by parts with use of the weight factor of triangle,

$$P = P(545) + P(550) = 100. \ [mW/m^2] \qquad (3)$$

That is, if the responsivity function of monochrometer has a shape of ideal isosceles triangle, the above-mentioned weighed integration can be performed precisely by making the half width of wavelength of responsivity function agrees with the wavelength sampling interval.

Further, it is also a problem to shorten a calculation time because the amount of calculation needed for energy integration with use of the measured values with use of the photosensor array is large for a prior art calculation procedure. In order to obtain an effective quantity such as illuminance and chromaticity, a convolution integration with a spectral function such as luminous efficacy curve or color matching function is performed. Because the above-mentioned spectroradiometer is utilized for spectroscopic analyses, it is designed primarily for observing spectroscopic profile with high wavelength resolution, and the wavelength sampling intervals and the half-bandwidths of the responsivity function are designed as narrow as possible. For example, if the visual wavelength range is measured with a photodiode linear array of 512 channels, the wavelength distances in the array are of the order of about 0.8 nm if we assume that there is no distortion of dispersion on the photosensor surface.

If the wavelength sampling intervals of such a spectral function do not agree with the measured wavelength sampling intervals, the matching between them has to be realized in the convolution integration. (For example, JIS Z8724-1983 defines that the color matching function is calculated with 5 nm of wavelength sampling intervals.) If we make the color matching function correspond with the center-of-gravity wavelengths of each photosensor element with use of interpolation, the convolution integration of 80 data and 80 data corresponds that of 512 data and 512 data under 5 nm of wavelength sampling intervals, so that the amount of calculation increases remarkably. For example, if the illuminance of a lamp is evaluated, such an integration has to be repeated at many wavelengths, for example for three primary colors, fifteen comparison colors and a standard wavelength.

Further, even if the resolution is improved, the precision of calculation can not improved, as will be explained below. If the emission spectrum and the color matching of light source of spectral measurement are designated as $E(\lambda)$ and $W(\lambda)$, respectively, an effective quantity P such as a photometry quantity or tristimulus values is obtained by the following equation:

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$$P = K \int_{-\infty}^{\infty} E(\lambda)W(\lambda)d\lambda, \quad (4)$$

wherein K is a constant. The sampling wavelength intervals of $E(\lambda)$ have to be values which assure sufficient precision when the integration in Eq. (4) is performed. If the functions obtained by the Fourier transformation of $E(\lambda)$ and $W(\lambda)$ are designated as $F(\omega)$ and $G(\omega)$, respectively,

$$F(\omega) = \int_{-\infty}^{\infty} E(\lambda)e^{-j\omega\lambda}d\lambda, \quad (5)$$

and

$$G(\omega) = \int_{-\infty}^{\infty} W(\lambda)e^{-j\omega\lambda}d\lambda, \quad (6)$$

wherein ω is a space frequency of the inverse of λ. If we take that $F(\omega)$ is the conjugate complex number of $F(\omega)$, Eq. (4) is transformed into the following equation:

$$\int_{-\infty}^{\infty} E(\lambda)W(\lambda)d\lambda = \frac{1}{2\pi}\int_{-\infty}^{\infty} F(\omega)G(\omega)d\omega. \quad (7)$$

In Eq. (5), if high-frequency components of $G(\omega)$ attenuates to zero faster than those of $F(\omega)$, the definite integration completes at a limit ω_0 even if $F(\omega)$ has any value at higher frequencies than ω_0. That is, if the emission spectra $E(\lambda)$ has any complex profile in Eq. (4), the high frequency components of $W(\lambda)$ higher than the upper limit ω_0 do not contribute to the weighed integration. Therefore, the maximum value h of the wavelength sampling intervals for performing the integration with a sufficient precision is given by the sampling theorem as follows:

$$h = 1/2\omega_0. \quad (8)$$

If the Fourier transformation of color matching functions $X(\lambda)$, $Y(\lambda)$ and $Z(\lambda)$ to be used to obtain a light source color or an object color is performed in a wavelength range between 400 and 760 nm, the amplitude becomes 10^{-4} at the fortieth harmonic wave. If the value is taken as a practical conversion value, 5 nm of the wavelength sampling interval is sufficient for determining an light source color or an object color, and even if the calculation is performed with a better resolution, the precision can not be improved though the steps of the calculation increases. Therefore, in order to obtain an effect quantity efficiently from the measured data as mentioned above, it is necessary to convert the data with 0.8 nm of intervals into the of 5 nm of wavelength sampling interval with use of the band characteristic of isosceles triangle of 5 nm half-bandwidth wavelength.

Further, when the wavelength intervals for measurement are narrow, the light for the measurement becomes weak. Still further, if a light source such as a fluorescent lamp having both mercury line spectra and continuous spectra of fluorescent material is measured, the dynamic range of the measurement system has to be made wide. Therefore, these factors also contribute errors.

SUMMARY OF THE INVENTION

It is an object of the present invention to decrease measurement errors caused by the mismatching of wavelength sampling intervals of effective curve with the spectral half-bandwidth.

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It is another object of the present invention to provide an improved electrophotographic imaging device with automatic calibration function.

In order to decrease errors in spectral measurement, the following two methods can be adopted according to the present invention: (1) the spectra of object light is measured and the convolution integral of the obtained data and a spectral effect curve is performed to obtain the effect quantity, the data measured at sampling intervals smaller than the wavelength sampling intervals of the spectral data of an effect curve are changed to data of wavelength sampling interval of spectral effect curve, and further are transformed so as to match the half-bandwidth of wavelength, and (2) if measured half-bandwidth of wavelengths are different from measured wavelength sampling intervals, the spectral data at wavelengths in correspondence with the wavelength sampling intervals are obtained with use of interpolation, and an effective quantity is obtained with a convolution integration with the spectral function, whereby the measurement precision is improved at any part in the whole wavelength range for spectral measurement without causing excess or lack of spectral information (data).

That is, data measured at intervals smaller than the wavelength sampling intervals of the spectral function are summed by using weight factors determined as the difference of the absolute value of the difference between the measured center-of-gravity wavelength and the center-of-gravity wavelength of the spectral function with the wavelength sampling intervals of the spectral function, and the measured data are converted to data at the wavelength sampling intervals to obtain the effect quantity. Further, if the measured wavelength half-bandwidths are different from the measured wavelength sampling intervals, the measured spectral data are interpolated to obtain spectral data at wavelengths at which the measured half-bandwidth corresponds to the wavelength sampling intervals, and the convolution integration with the spectral function is performed to obtain the effective quantity.

In a spectroradiometer according to the present invention, a plurality of line spectra of specified wavelengths obtained from a light source are introduced into the spectroradiometer, and addresses in correspondence to theoretical positions of the elements of the linear photosensor array at which a maximum photoelectric output can be obtained are determined for each line spectrum. Then, an element which outputs a maximum photoelectric signal for a line spectrum is determined among the elements around the address, and the photoelectric outputs with use of the address as a weight factor are integrated as to the elements which belong in a range double the mechanical width of transmission band region of the spectroradiometer around the above-mentioned element of the maximum signal. The integrated value is divided by another integrated value obtained similarly except that the weight factor is taken as one. Then, the address of the photosensor array for each line spectrum is determined, and the center-of-gravity wavelengths of each element are calculated from the wavelengths of line spectra and the regression curve of the address of the photosensor array in correspondence to the line spectra.

It is an advantage of the present invention that energy integration can be performed precisely for spectral measurement.

It is another advantage of the present invention that calculations with use of measured values of optical spectra can be performed in a short time.

It is a further advantage of the present invention that the wavelength scale of a spectroradiometer can be calibrated automatically.

BRIEF DESCRIPTION OF THE DRAWINGS

These and other objects and features of the present invention will become clear from the following description taken in conjunction with the preferred embodiments thereof with reference to the accompanying drawings throughout which like parts are designated by like reference numerals, and in which:

Fig. 1 is a diagram of a trapezoid characteristic of a mercury line spectrum of 546.07 nm;

Fig. 2 is a diagram of an isosceles characteristic of photosensor array for a mercury line spectrum of 546.07 nm;

Fig. 3 is a diagram of an optical system of a multi-channel spectroradiometer;

Fig. 4 is a diagram for showing the deviations of center-of-gravity wavelengths of each element of linear photosensor array from equivalent interval wavelength scale;

Fig. 5 is a schematic block diagram of wavelength calibration;

Fig. 6 is a graph of the deviations of the measured center-of-gravity wavelengths from the theoretical center-of-gravity wavelengths which are derived by assuming 0.9 nm wavelength intervals of the photosensor elements;

Fig. 7 is a graph of the deviations of the measured center-of-gravity wavelengths from the theoretical center-of-gravity wavelength which is derived by assuming 0.9 nm wavelength intervals of the photosen-

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sor elements;

Fig. 8 is a graph of wavelength band characteristic of sensitivity of each element and the synthesized characteristic thereof around 550 nm wavelength in a multi-channel spectral measurement apparatus;

Fig. 9 is a diagram for displaying a conversion method to band characteristic W_λ of sensitivity of center-of-gravity wavelength λnm and 5 nm half width of wavelength band;

Fig. 10 is a graph of responsivity function of measured values when a slit width is synthesized;

Fig. 11 is a graph of the deviation of the results from the reliable data measured by the accurate spectroradiometer which uses the mechanical wavelength scanning type double prism monochrometer;

Fig. 12 is a graph of responsivity function of each element and the synthesized characteristic thereof when the matching between the wavelength half-bandwidths of responsivity function of each element and wavelength widths (measured sampling intervals of wavelength) of each element; and

Fig. 13 is a graph of spectral data at positions of wavelength intervals equal to wavelength half-bandwidth of responsivity function of each element obtained with interpolation from spectral measurement data.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Embodiments of the present invention will be explained with reference to drawings.

Example 1

First, a spectroradiometer in combination of a concave diffraction grating and a photodiode linear array is explained. Fig. 3 shows an optical system of a multi-channel spectoradiometer including a concave diffraction grating 1 of 300 grooves/mm of groove density, 500 nm of blaze wavelength and 200 mm of focal distance (f) and a linear photosensor array 2 of silicon photodiodes (512 elements). A concave diffraction grating 1 has combined functions of a planar diffraction grating, a collimator mirror and a focusing mirror. If an entrance slit 4 of the concave diffraction grating 1 is provided on a circle (Rowland circle 3) having a diameter equal to the curvature diameter of the concave diffraction grating 1, a spectral dispersion image is focused on the Rowland circle 3. Therefore, a spectroradiometer can be constructed with use of the concave diffraction grating 1 more simply and compactly, and it is possible that a change in linear dispersion can be made relatively smaller.

In the multi-channel spectroradiometer shown in Fig. 3, a light from a light source or an object is introduced from an entrance slit 4 provided on the Rowland circle 3 at 11.8° of incident angle from the center normal line of the grating 1. In order to detect the diffracted light on the normal dispersion region of the concave diffraction grating 1, the detection region is determined to be an angular region wherein the diffraction angle β between the center normal line and the diffracted light is set between -4.8° and +2°. Under the above-mentioned conditions, the wavelengths of the dispersion pattern are within 400 to 800 nm of wavelength on the Rowland circle. Because the linear dispersion is 0.0600 (mm/nm) on the center normal line and 0.0608 (mm/nm) at $\beta = -4.8°$, a change in linear dispersion in the detection region is 1.3 % or less between 400 and 800 nm. Then, if the center of the linear photosensor array 2 is set on the center normal line and on the Rowland circle 3, the wavelength intervals of the elements of the linear photosensor array 1 around the center of the linear photosensor array 2 is $0.06 \times 54 = 0.9$ nm owing to the value of linear dispersion at the position and the spacial interval (54 μm) of the elements.

The change of wavelength intervals of the sensor elements located towards each end of the visible region are calculated analytically as follows: Fig. 4 shows the deviation of the center-of-gravity wavelengths of each sensor element from equal wavelength interval scale in three cases: a case that the photodiode array 2 makes contact with the Rowland circle 3, a case that it is placed 0.5 mm inside from the Rowland circle 3, and a case that it is placed outside from the Rowland circle 3. Fig. 4 shows clearly that even when the sensor is tangent to the Rowland circle 3, the center-of-gravity wavelengths of each sensor element are not settled at equal intervals, and the deviations become larger at shorter and longer wavelength regions. This effect is particularly pronounced when sensor elements are positioned away from the Rowland circle 3. Therefore, the center-of-gravity wavelengths of each sensor element have to be individually determined.

Four mercury line spectra of low-pressure mercury discahrge lamp at wavelengths of 404.66, 435.84, 546.07 and 578.01 nm and three line spectra of neon lamp of wavelengths of 614.91, 639.48 and 703.24 nm are used for calibration.

Fig. 5 shows a schematic diagram of wavelength calibration. The mechanical width of the entrance slit 4 of 50 μm is used. Then, the wavelength half-bandwidth of an element at the center of the wavelength band of measurement becomes 0.9 nm which is also equal to the measured wavelength interval. Therefore, errors of photometry and of colorimetry decrease.

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The linear photosensor array 2 consists of a silicon photodiode array 2a and a charged-coupled detector 2b. Under these conditions, in an example, the output signals of the silicon photodiode array 2a for dispersion light of mercury line spectrum of wavelength 546.07 nm is displayed in Fig. 6.

A conventional computer 8 having a central processing unit, a ROM for storing a program for wavelength calibration and a RAM for work area performs wavelength calibration according to the measured data received form the charge-coupled-device 2b to detect the diffracted light. First, linear dispersion is obtained from the constants of the optical system, and the theoretical address of an element at which a maximum photoelectric output is obtained in correspondence to the mercury line spectrum of wavelength 546.07 nm is calculated (block 9). The calculation shows that the output signal is expected to attain maximum around address 200. Next, in order to get an actual address of an element for a maximum value, an address at the element is detected by observing the output signals of element addresses between 190 and 210 around the theoretical address (block 10). Then, the center-of-gravity wavelength at each address is calculated as explained below. The output $P(x_m)$ of an element of address x_m is maximum. If the wavelength half-bandwidth of sensitivity is about 0.9 nm, this corresponds with the mechanical width by two elements if we take the tail of responsivity function into account. The center address Ad for wavelength 546.07 nm is calculated with use of the following equations in a range between -3 and +3 against the element address x_m by taking the distortion of dispersion into account:

$$A = -3*P(x_m-3) - 2*P(x_m-2) - 1*P(x_m-1) + P(x_m) + P(x_m+1) + 2*P(x_m+2) + 3*P(x_m+3), \quad (9)$$

$$B = P(x_m-3) + P(x_m-2) + P(x_m-1) + P(x_m) + P(x_m+1) + P(x_m+2) + P(x_m+3), \quad (10)$$

and

$$Ad = A/B. \quad (11)$$

In other words, A is obtained by integrating the photoelectric outputs of elements with use of the addresses of element as weight factors, which elements including the element of the maximum photoelectric output as the center and its neighboring elements at least in a range of double the mechanical transmission band width (block 11), while B is obtained by integrating the same photoelectric outputs without use of the addresses of element as weight factors (block 12). Then, the address Ad in correspondence with center-of-gravity wavelength of said photosensor array for each line spectrum relative to x_m is obtained by dividing the value A of weighed integration with the value B. That is, the obtained center address is equal to x_m + Ad (block 13).

As to the other six line spectra, the center addresses are also obtained similarly.

Next, a regression curve is calculated, and the center-of-gravity wavelengths of each of 512 photosensor elements are calculated. Then, wavelength calibration of spectroradiometer is completed.

Thus, the spectroradiometer according to the present embodiment has a wavelength calibration function that the center-of-gravity wavelengths of each element of the photosensor array 2 are determined from the plurality of line spectrum wavelengths for calibration and the actual addresses of the elements of the linear photosensor array 2 in correspondence with the line spectrum wavelengths.

Fig. 6 shows the deviations of the measured center-of-gravity wavelengths from the center-of-gravity wavelength calculated by assuming 0.9 nm equal wavelength intervals of the sensor elements. The result shows larger positive deviations at longer wavelengths. When compared with the results shown in Fig. 5, this measured data is similar to the case where the sensor elements are placed inside the Rowland circle 3.

As explained above, in a spectroradiometer or the like wherein a spectral dispersion optical system and a linear photosensor array is combined to measure optical spectra of an object in a short time, even if the nonlinearity is large on a plane on the linear photosensor array, the precision of photometry and of colorimetry is improved by using the above-mentioned wavelength calibration which uses line spectrum radiations at a plurality of wavelength to obtain a regression curve of the addresses of each element with wavelength and to set the center-of-gravity wavelengths of each elements.

Especially, when wavelength is calibrated with use of each line spectrum, erroneous recognition of line spectrum due to stray light and noises of spectroradiometer are prevented and the precision of wavelength calibration is improved.

Example 2

If a multi-channel spectroradiometer of the above-mentioned type shown in Fig. 3 is used for

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photometry and for colorimetry, the relation between the center-of-gravity wavelength of spectral responsivity of each photosensor element and the dispersion characteristic and the intervals (wavelength sampling intervals) of each photosensor element affect the precision of measurem nt.

When the entrance slit 4 is positioned on the Rowland circle 3, the diameter of the circle 3 coincides with the radius of curvature of the concave diffraction grating 1, and the dispersion pattern is focused on the Rowland circle 3. However, all of the photosensor elements of linear photosensor array 2 cannot be positioned on the curved surface of the Rowland circle 3, and they are aligned on a planar surface. Thus, the responsivity function (band characteristic of sensitivity) and the center-of-gravity wavelengths of each element of the linear photosensor array 2 depend largely on the wavelength, resulting in large errors in colorimetry or the like.

In order to obtain a precise energy integration from the spectral data, exact matching between the wavelength sampling intervals and the half-bandwidths has to be accomplished.

Fig. 8 shows the measured responsivity function of each element (responsivity function g_1, g_2, ..., g_5) and the synthesized characteristic thereof (synthesized responsivity function $g_1 + g_2 + g_3 + g_4 + g_5$) around 550 nm wavelength of a multi-channel optical measurement apparatus comprising a concave diffraction grating of 200 mm focal distance and 1/150 mm groove distance and a photodiode linear array 2 of 50 μm of element distance. The entrance slit 4 of the spectral measurement apparatus is set as 50 μm. The intervals between center-of-gravity wavelengths of each element are set about 0.9 nm, and the synthesized characteristic of responsivity functions of each element is found to have a nearly flat characteristic.

This means that whatever spectral distribution of a light source is, an exact energy evaluation can be done over the measured spectral relation. As shown in Fig. 2, if the wavelength half-bandwidths of responsivity function of isosceles triangle agree with the wavelength sampling intervals, the energy of a line spectrum can be measured without excess or lack by synthesizing the observed values at two spectral bands including the wavelength of the line spectrum. This is true irrespective of wavelength of line spectrum. That is, the synthesized value lies on a linear line connecting the apexes of the triangular bands, and the line is a locus of the measured value of the line spectrum when wavelength is changed under a constant energy. In other words, if the synthesized value becomes linear as shown in Fig. 8, the energy component at any wavelength can be evaluated without excess or lack. Therefore, the linearity of the synthesized value of each spectral band is a necessary condition in order to get a precise measured value with use of the isosceles triangular spectral bands. On the contrary, if the half-bandwidths of responsivity function do not agree with wavelength sampling intervals, the synthesized value does not become flat against wavelength, so that errors arise in a measurement

Fig. 9 displays a process for conversion to a responsivity function (synthesized responsivity function) W_λ of λ nm of the center-of-gravity wavelength and 5 nm of half-bandwidth of wavelength band. Only the elements which exist within the half-bandwidth 5 nm or satisfy the following relation contribute the synthesis of responsivity function:

$$|\lambda - \lambda_j| \leq 5. \quad (12)$$

In the case shown in Fig. 9, the center-of-gravity wavelengths of each element in the wavelength range of responsivity function W_λ between λ_{-6} and λ_5 around a central band of λ_0 including the wavelength λ are taken into acount, and W_λ is given by the following equation:

$$W_\lambda = \sum_{f}^{g} (5 - |\lambda - \lambda_j|) W_j/5, \quad (13)$$

wherein f = -6 and g = 5 and W_j is the output of photosensor element at wavelength λ_j. In this process, the data W_j measured at intervals about 0.9 nm smaller than the wavelength sampling intervals 5 nm of the spectral data are summed by using weight factors $(5 - |\lambda - \lambda_j|)/5$ determined as the difference of the absolute value of the difference between the measured center-of-gravity wavelength of the center element of the maximum output and a center-of-gravity wavelength of the spectral data to be obtained with the wavelength sampling intervals of the spectral data.

Fig. 10 shows a measured responsivity function when the slit width (wavelength range) is synthesized with the above-mentioned process. It is apparent that the isosceles triangle characteristic of 5 nm wavelength half-bandwidth can be realized.

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By using the above-mentioned multi-channel spectroradiometer, chromaticities of three types of fluorescent lamps (FL40WW, FL40W.SDL and FL40ss.EX) are measured. Fig. 11 shows the deviations of the measured chromaticities from those measured by an accurate spectroradiometer comprising a mechanical wavelength scanning type double prism monochrometer.

When the center-of-gravity wavelength of each elements are calibrated and the responsivity function synthesis is carried out, the measured results agree well with the reliable data obtained by the accurate spectroradiometer within ±0.0015 differences on a UCS color diagram. However, without the center-of-gravity wavelength calibration and the responsivity function synthesis, the results deviate from the reliable data by more than 0.006.

The results indicate that the center-of-gravity wavelength calibration and the responsivity function synthesizing process are good for error reduction in the above-mentioned multi-channel spectroradiometer.

Example 3

Next, a third embodiment of the present invention will be explained below.

In the above-mentioned multi-channel spectral measurement apparatus in combination of a concave diffraction grating 1 and a linear photosensor array 2, if the widths of dead zone 21 between each element 22 become so large and can not be neglected against the widths of elements, the matching of the wavelength half-bandwidths of responsivity function of each element with the wavelength widths of each element (wavelength sampling intervals) becomes worse as shown in Fig. 12.

Then, as shown in Fig. 13, spectral data at positions having wavelength intervals equal to the wavelength half-bandwidth of responsivity function of each element is obtained by using interpolation from the measured spectral data around the center-of-gravity wavelength positions, for example with use of Lagrange's interpolation method. In a case shown in Fig. 13, if the isosceles triangle characteristic of 555 μm is taken as a data as it is, an interpolated value of the next frequency below 555 μm by the wavelength half-bandwidth does not correspond with 550 μm of adjacent sampling wavelength. Then, the spectral data at the interpolated frequency is obtained by the interpolotion of the data at 555 and 550 μm. Therefore, spectral data can be matched with the wavelength half-bandwidth of responsivity function with the measured wavelength sampling intervals.

The matching between spectra data and wavelength intervals of data of spectral effect curve such as color matching can be realized further with the method explained in the second embodiment.

Although the present invention has been fully described in connection with the preferred embodiments thereof with reference to the accompanying drawings, it is to be noted that various changes and modifications are apparent to those skilled in the art. Such changes and modifications are to be understood as included within the scope of the present invention as defined by the appended claims unless they depart therefrom.

Claims

1. Method of spectral measurement, wherein the spectra of object light is measured with an optical system including a linear photosensor array and an effect quantity is obtained by the convolution integral of the obtained data and a spectral effect curve, comprising the step of:

   obtaining the photoelectric outputs of the elements consisting of said linear photosensor array, said elements being arranged at first wavelength sampling intervals; and

   converting the photoelectric output data measured at the first wavelength sampling intervals to data of the effect quantity of the second wavelength sampling intervals of the spectral data larger than the first wavelength sampling intervals by summing the output photoelectric data of the elements for each sampling point of the effect quantity with use of weight factors determined as the absolute value of the difference between the canter-of-gravity wavelength at the sampling point of the spectral data and the center-of-gravity wavelengths of the elements.

2. Method of spectral measurement according to claim 1, further comprising for wavelength calibration the steps of:

   determining a first address in correspondence with the theoretical position of an element of said linear photosensor array for which a maximum photoelectric output for each line spectrum is expected according to linear dispersion;

   determining a second address of an element at which the photoelectric output is maximum among elements around the first address;

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integrating the photoelectric outputs to obtain a first integrated value for a line spectrum of elements of said linear photosensor array with use of weight factors in relation to addresses of the element of the second address and of neighboring elements thereof included at least in a range double the mechanical width of the entrance slit;

integrating the photoelectric outputs to obtain a second integrated value for a line spectrum of elements of said linear photosensor array with use of weight factors of one in relation to addresses of the element of the second address and of neighboring elements thereof included at least in a range double the mechanical width of the entrance slit;

determining a third address in correspondence with the center-of-gravity wavelength of said linear photosensor array for each line spectrum by dividing the first integrated value by the second integrated value; and

determining the center-of-gravity wavelengths of each element of said linear photosensor array according to wavelengths of said plurality of line spectra for calibration and the third addresses of said photosensor array in correspondence with the line spectra,

whereby the calibrated center-of-gravity wavelengths are used in the processing of measured spectral data .

3. Method of spectral measurement, wherein the spectra of object light is measured and the convolution integral of the obtained data and a spectral effect curve is performed to obtain the effect amount, comprising the step of:

interpolating the measured spectral data to obtain spectral data at wavelengths at which the measured half-bandwidth corresponds to the measured wavelength sampling intervals if the measured wavelength half-bandwidth is different from the measured wavelength sampling intervals, and

performing the convolution integration of the obtained data and a spectral effective curve to obtain the effect amount.

4. A spectroradiometer, comprising:

entrance means, including an entrance slit, for introducing light received from an object or from a light source of line spectra for calibration which radiates a plurality of line spectra at specified wavelengths;

dispersion means for dispersing spectrally the light introduced by said entrance means;

a linear photosensor array for converting the light dispersed by said dispersion means into an electric signal;

first address-determining means for determining a first address in correspondence with the theoretical position of an element of said linear photosensor array for which a maximum photoelectric output for each line spectrum is expected according to linear dispersion determined by said dispersion means;

second address-determining means for determining a second address of an element at which the photoelectric output is maximum among elements around the first address determined by said first address-determining means; and

calculating means for calculating center-of-gravity wavelengths at each address with height factors including addresses of the elements.

5. A spectroradiometer according to claim 4, wherein said calculating means comprises:

first integration means for integrating the photoelectric outputs for a line spectrum of elements of said linear photosensor array with use of weight factors in relation to addresses of the element of the second address and of neighboring elements thereof included at least in a range double the mechanical width of the entrance slit;

second integration means for integrating the photoelectric outputs of a line spectrum of elements of said linear photosensor array with use of weight factors of one in relation to addresses of the element of the second address and of neighboring elements thereof included at least in a range double the mechanical width of the entrance slit;

third address-determining means for determining a third address in correspondence with the center-of-gravity wavelength of said linear photosensor array for each line spectrum by dividing the integrated value of said first integration means for the line spectrum by the integrated value of said second integration means for the line spectrum; and

means for determining the center-of-gravity wavelengths of each element of said linear photosensor array according to wavelengths of said plurality of line spectra for calibration and the third addresses of

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said photosensor array in correspondence with the line spectra.

6. A spectroradiometer according to claim 4, wherein the wavelength width of said entrance slit is set to be equal to the wavelength intervals of elements of said linear photosensor array.

7. A spectroradiometer according to claim 4, wherein said dispersion means includes a concave diffraction grating.

8. A spectroradiometer according to claim 4, wherein said entrance slit for said dispersion means is provided on the Rowland circle of said concave diffraction grating.

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Fig. 1

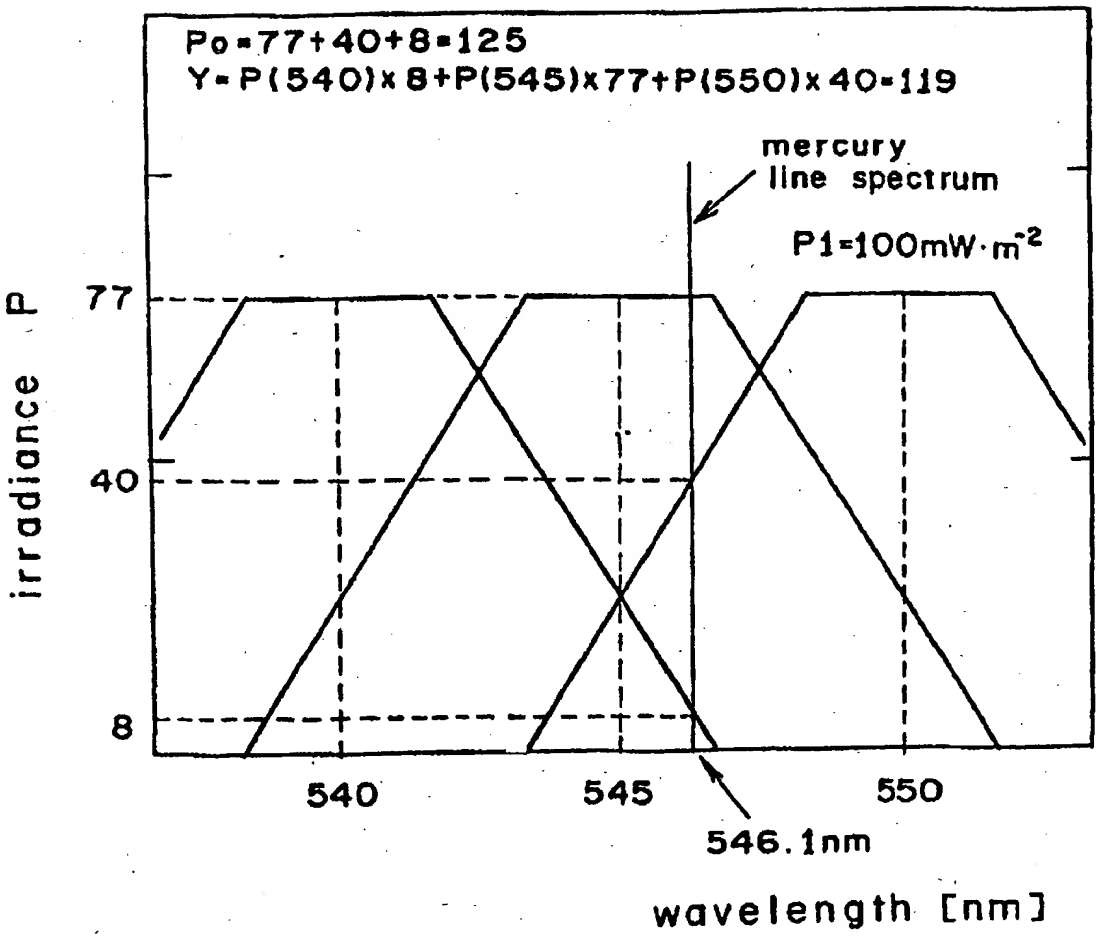

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Fig. 2

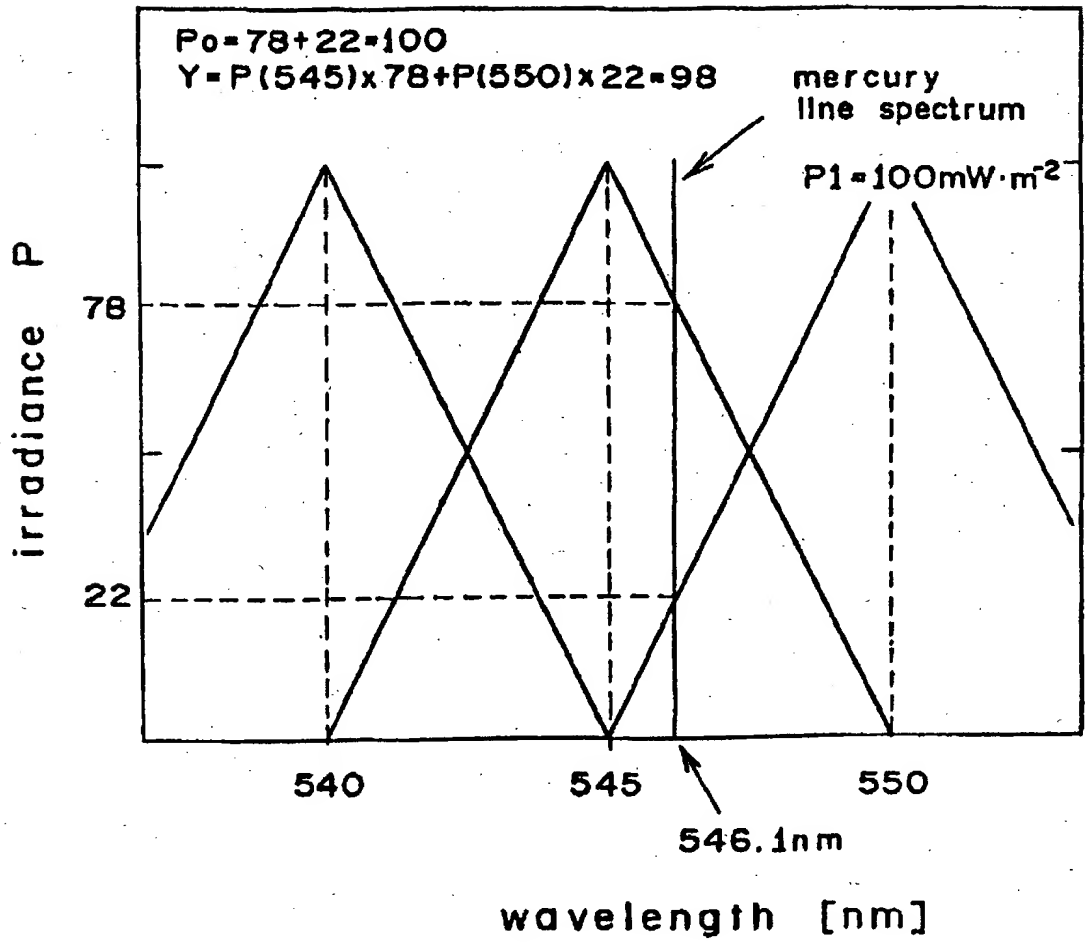

Po=78+22=100
Y=P(545)x78+P(550)x22=98
mercury
line spectrum
P1=100mW·m-2
irradiance P
78
22
540
545
550
546.1nm
wavelength [nm]

Fig. 3

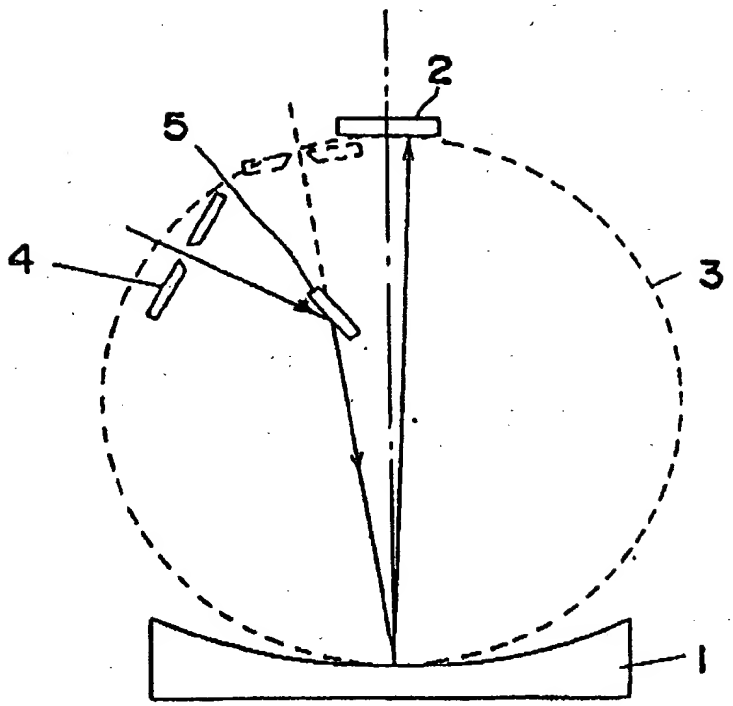
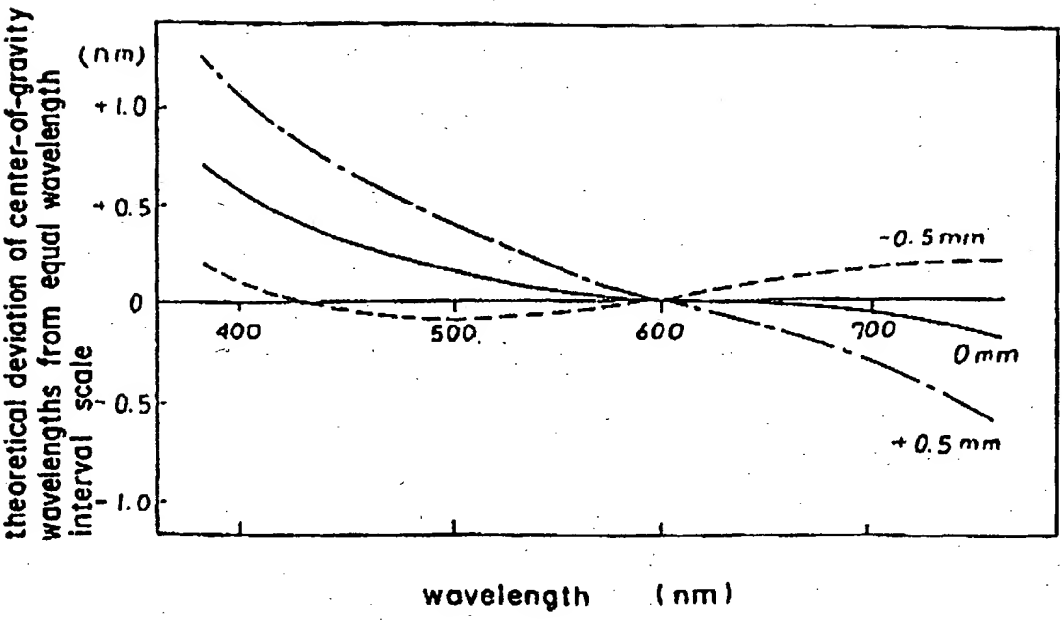


Fig. 4


theoretical deviation of center-of-gravity wavelengths from equal wavelength interval scale
(nm)
+1.0
+0.5
0
-0.5
-1.0
400
500
600
700
-0.5mm
0mm
+0.5mm
wavelength (nm)

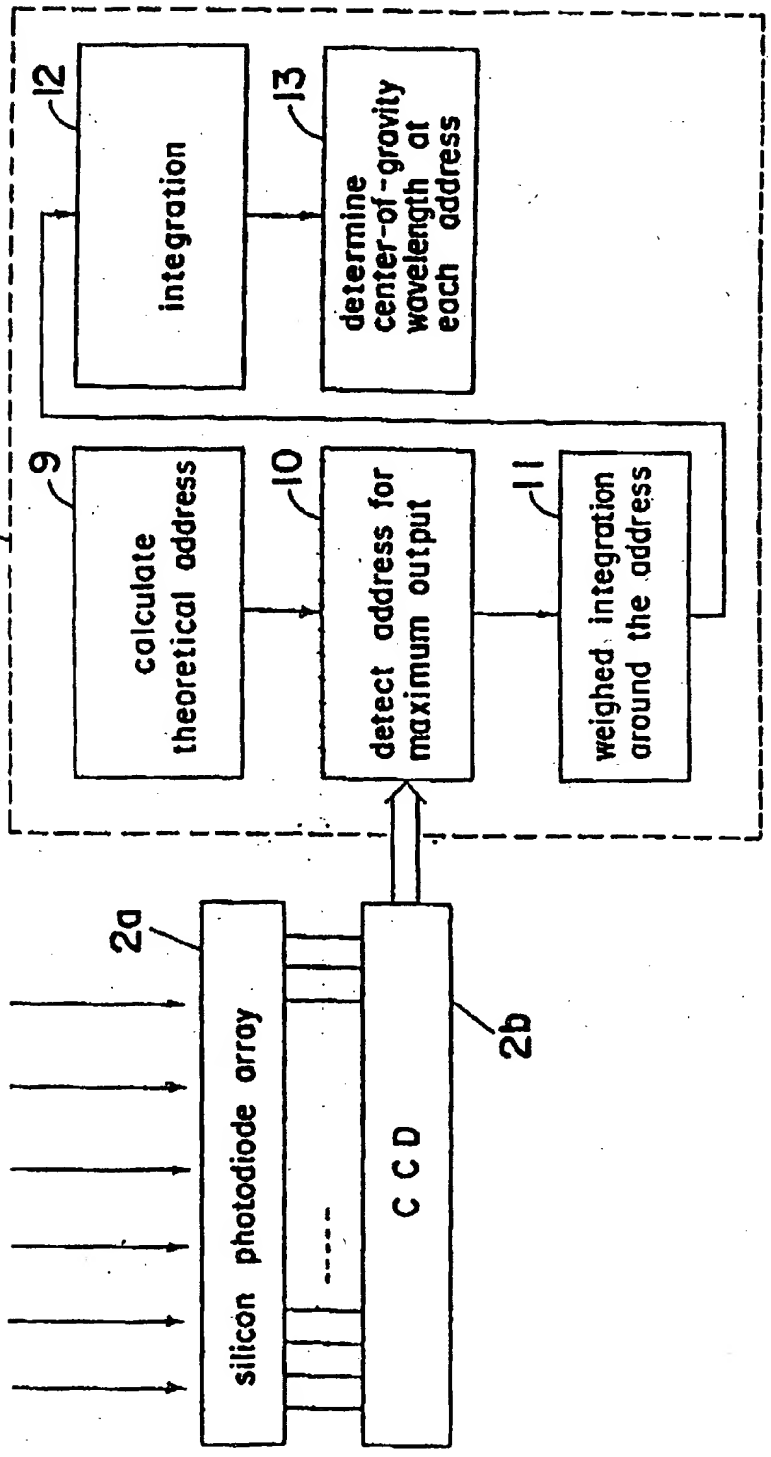


Fig. 5

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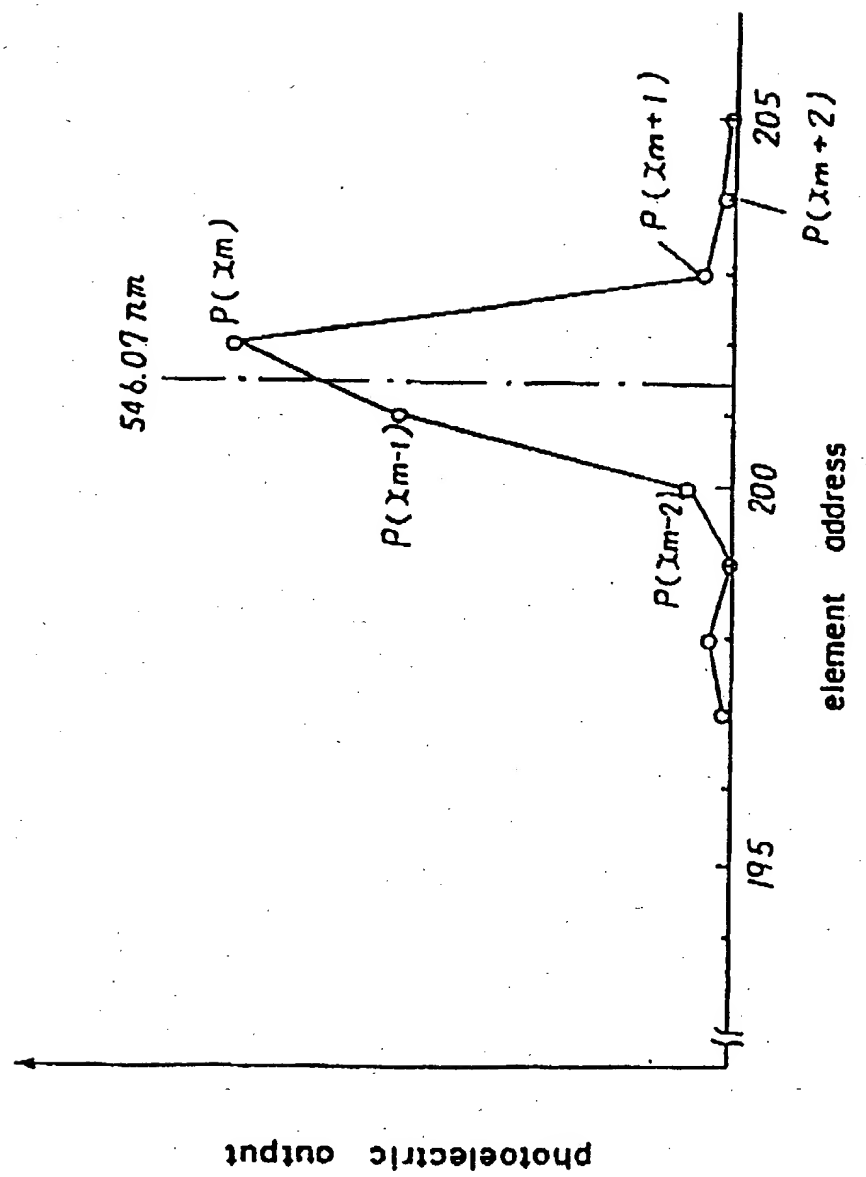
546.07 nm
P(λm)
P(λm-1)
P(λm-2)
P(λm+1)
P(λm+2)
195
200
205
element address
photoelectric output

Fig. 6

Fig. 7

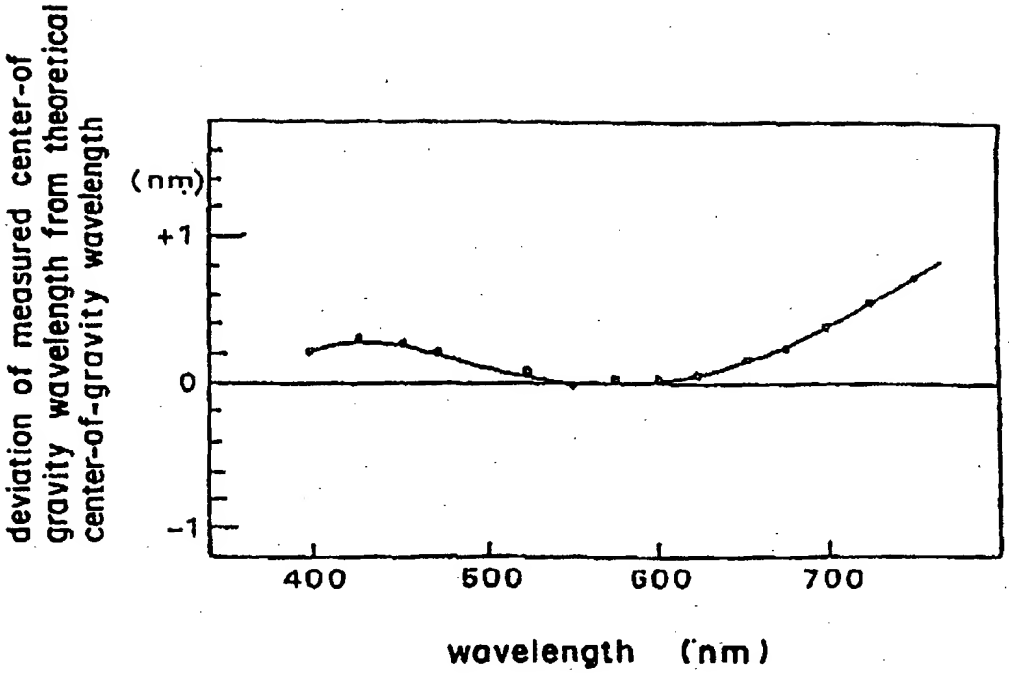

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Fig. 8

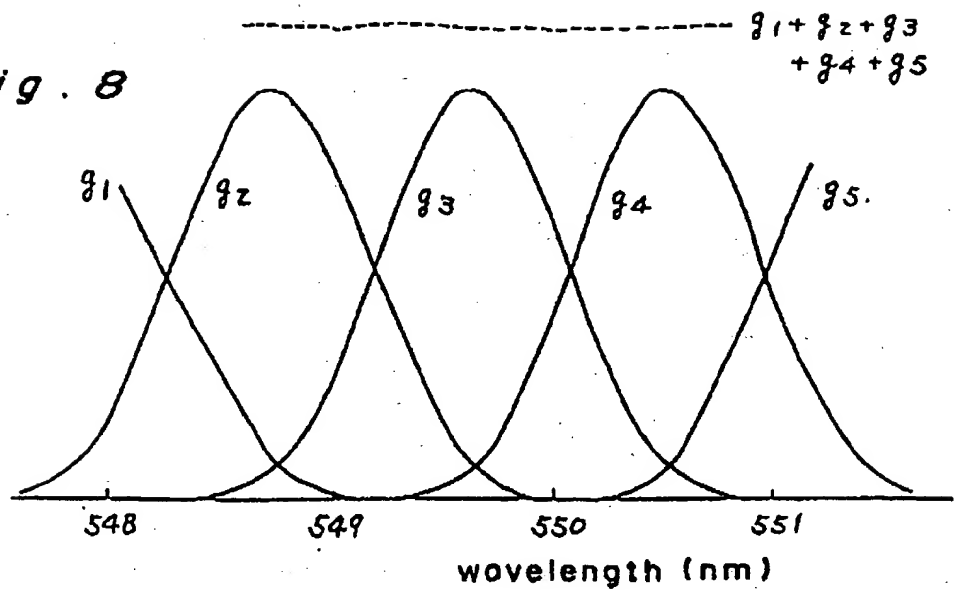

Fig. 9

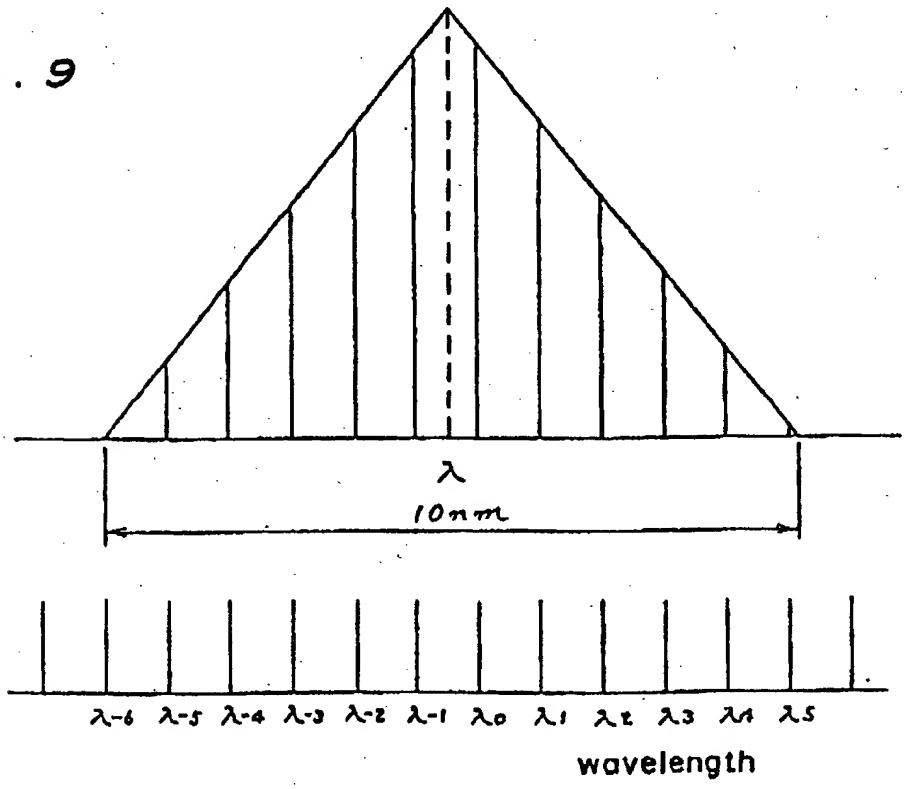

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Fig. 10

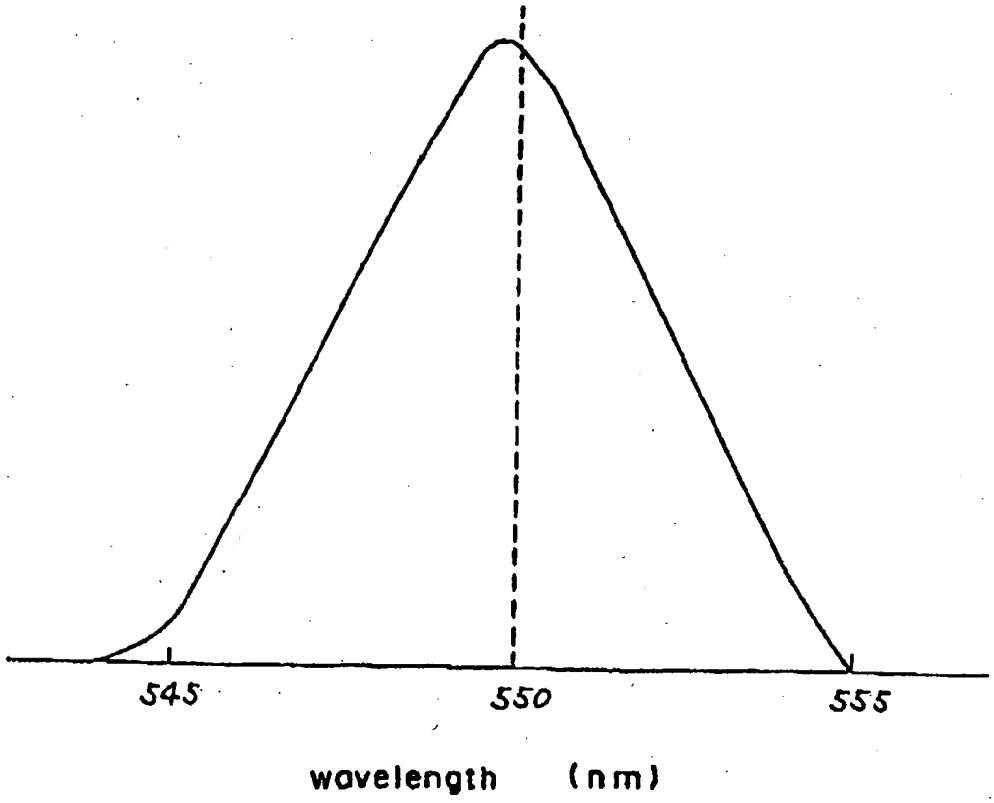

Fig. 11

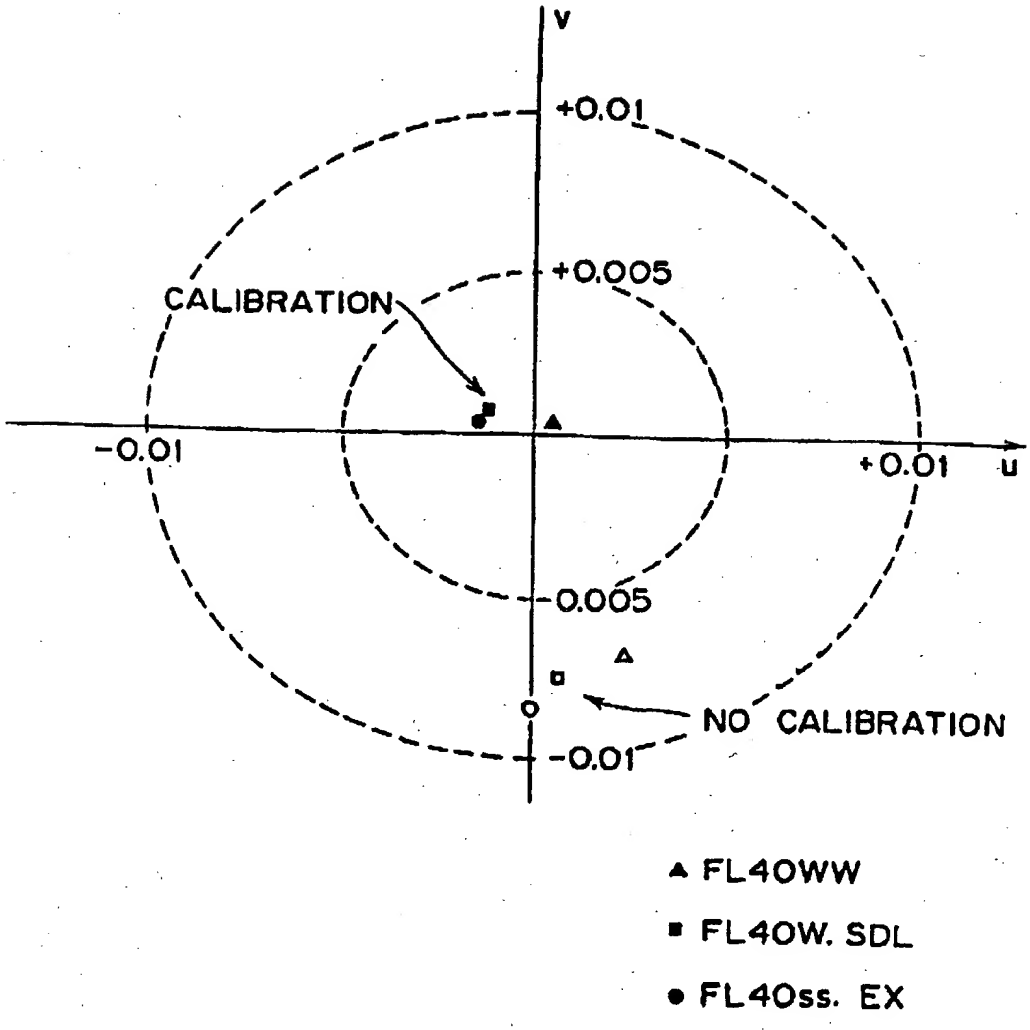
v
+0.01
+0.005
CALIBRATION
-0.01
+0.01
u
-0.005
o
NO CALIBRATION
-0.01
▲ FL40WW
■ FL40W. SDL
● FL40ss. EX

Fig. 12

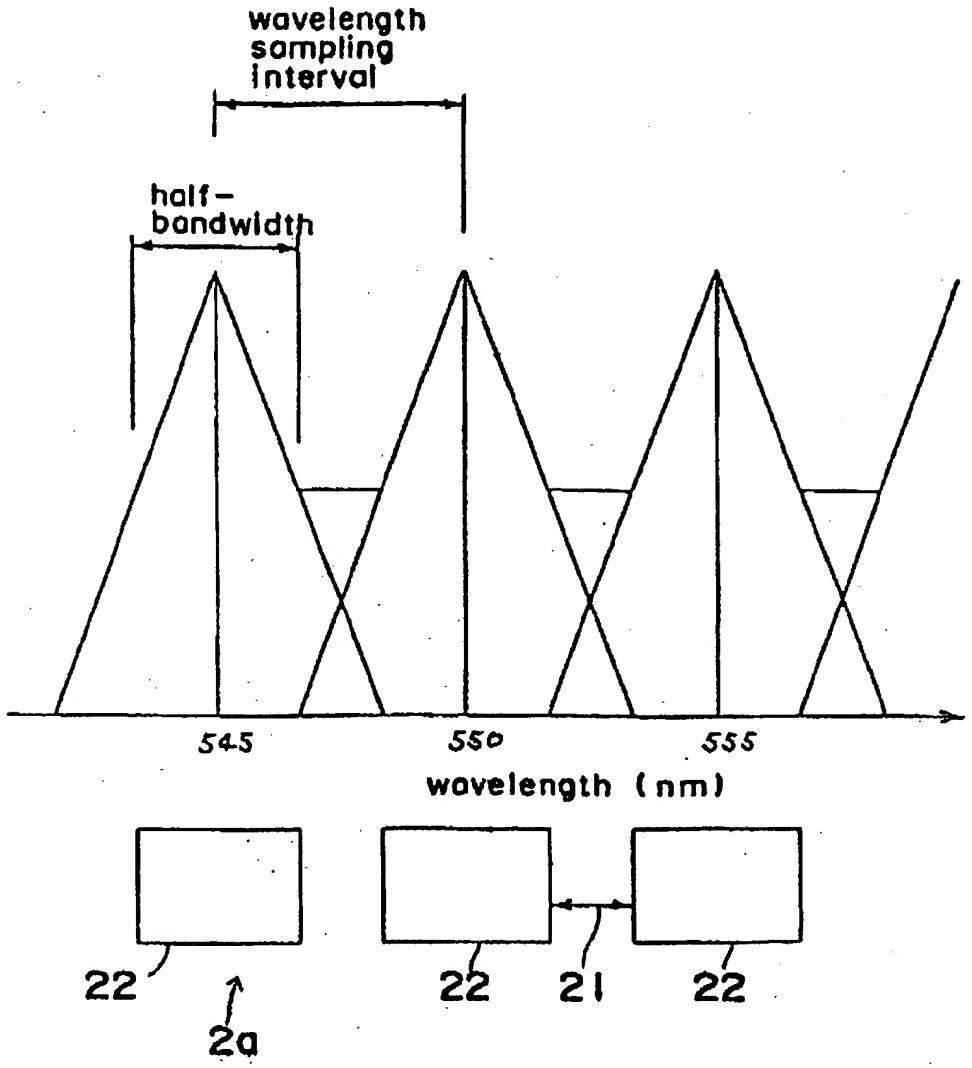

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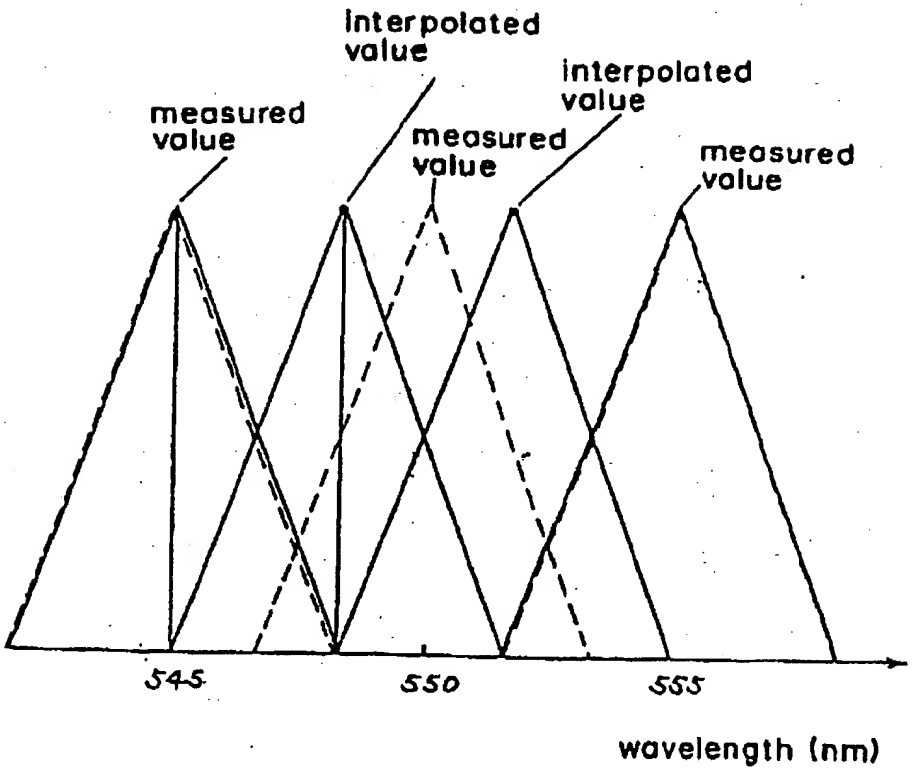
Fig. 13


interpolated value
interpolated value
measured value
measured value
measured value
545
550
555
wavelength (nm)

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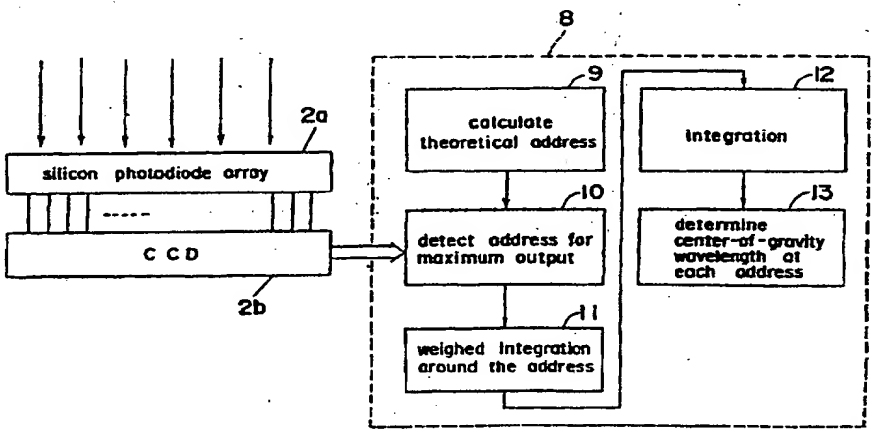
(54) Method of spectral measurement and spectroradiometer having wavelength calibration function.

(57) In order to decrease errors in spectral measurement, the data measured at sampling wavelength intervals smaller than the wavelength sampling intervals are changed to data of wavelength sampling interval of spectral effective curve.

If the wavelength half-bandwidths to be measured are different from the wavelength sampling intervals, the spectral data at wavelengths in correspondence with the wavelength sampling intervals are obtained with interpolation.

In a spectroradiometer, wavelength scale is calibrated with use of a plurality of line spectra of specified wavelengths, and the photoelectric outputs are integrated with use of the addresses of elements as a weight factor.

Fig. 5



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European Patent Office

EUROPEAN SEARCH REPORT

Application Number

EP91110401

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int. Cl.5)
X	US-A-4669880 (NELSON et al.) * abstract; column 2, line 44 - column 3, line 16; column 4, line 34 - column 5, line 23; figures 2,3 *	1,3	G01J3/28 G01J3/36
Y		2	
A		6	
X	US-A-4692883 (NELSON et al.) * abstract; column 8, line 55 - column 9, line 15; figures 3-5 *	4,5	
Y		2	
A	PATENT ABSTRACTS OF JAPAN vol. 12, no. 303 (P-746)(3150), 18 August 1988; & JP - A - 63075523 (MATSUSHITA ELECTRIC) 05.04.1988 * abstract *	7,8	TECHNICAL FIELDS SEARCHED (Int. Cl.5) G01J

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
Berlin	07.05.92	VON MOERS, F.

CATEGORY OF CITED DOCUMENTS

X : particularly relevant if taken alone
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O : non-written disclosure
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T : theory or principle underlying the invention
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CLAIMS INCURRING FEES

The present European patent application comprised at the time of filing more than ten claims.

☐ All claims fees have been paid within the prescribed time limit. The present European search report has been drawn up for all claims.

☐ Only part of the claims fees have been paid within the prescribed time limit. The present European search report has been drawn up for the first ten claims and for those claims for which claims fees have been paid, namely claims.

☐ No claims fees have been paid within the prescribed time limit. The present European search report has been drawn up for the first ten claims.

X LACK OF UNITY OF INVENTION

The Search Division considers that the present European patent application does not comply with the requirement of unity of invention and relates to several inventions or groups of inventions, namely:

1. Claims 1-3: Bandwidth conversion for a detector array spectrophotometer

2. Claims 4-8: Wavelength calibration for a detector array spectrophotometer

☒ All further search fees have been paid within the fixed time limit. The present European search report has been drawn up for all claims.

☐ Only part of the further search fees have been paid within the fixed time limit. The present European search report has been drawn up for those parts of the European patent application which relate to the inventions in respect of which search fees have been paid, namely claims:

☐ None of the further search fees has been paid within the fixed time limit. The present European search report has been drawn up for those parts of the European patent application which relate to the invention first mentioned in the claims, namely claims:

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